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Simulation and Numerical Analysis of the Explosion Effect on the Body of Earthen Dam in Injection Gallery

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ABSTRACT

This article focuses on modeling and numerical analysis of the effects of an explosion on the body of an earthen dam in an injection gallery. Earthen dams are crucial for water supply, electricity generation, and flood control but face risks like explosions from military operations, industrial accidents, and earthquakes. Explosions can cause severe damage, downstream flooding, and even dam failure, making risk identification and mitigation essential. The researchers aim to investigate the effects of explosions on the injection gallery of an earthen dam using Abaqus modeling software and Python for numerical analysis. The goal is to understand the behavior of earthen dams during explosions and provide solutions to reduce associated risks. The study presents the general characteristics of the dam, including its type, riverbed height, maximum dam height, and other parameters. Details of the injection gallery's construction, including its length and cross-sectional dimensions, are described. The explosion process and its consequences, such as energy release, gas production, and pressure waves, are also explained. A Reservoir Dam in Lorestan, Iran, is used as a case study, with detailed information about its characteristics provided in a table. The length and cross-section of the concrete and reinforced injection gallery are mentioned. This study helps to understand the response of earthen dams to explosions and suggests measures to reduce related risks. The modeling and numerical analysis offer valuable insights into the behavior of earthen dams under blast conditions and contribute to strategic development.

Keywords: Explosion, Earth dam, Injection gallery, Hazards, Numerical analysis

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1. INTRODUCTION

The article "Modeling and numerical analysis of the effect of the explosion on the body of an earthen dam in injection Gallery" deals with the investigation of the effect of the explosion on the body of an earthen dam. Earth dams play a very

important role in matters such as water supply for agriculture, electricity generation, and flood control. But these dams may also be affected by hazards, including explosions. An explosion in an earthen dam can have serious consequences, including severe

damage to the dam building, flooding under the dam, and even the destruction of the dam. Therefore, it is very important to identify and reduce the risks caused by this type of incident [1]. In this research, using Abaqus modeling and numerical analysis using Python, the effects of an explosion in the gallery an earthen dam will be tested. The main goal of the research is to better understand the behavior of earthen dams against explosion [1-6] and effective solutions are provided to reduce the related risks. For this purpose, modeling an earthen dam has been built in Lorestan province of Iran and the general characteristics of the dam are explained in the mentioned tables. Also, the technical specifications of the concrete used in the injection gallery, as well as the modeling in the Abaqus software, are given in another table [7]. In an explosion produces and releases energy quickly and causes an increase in the volume of the head. This volume increase along with gas production leads to production A pressure wave spreads out from the center of the explosion. [8-10] This pressure wave can destroy buildings and structures. Examining the effects of the explosion in the injection gallery of the earthen dam is of great importance, because it can lead to a better understanding of the behavior of the dam in the face

of the explosion and provide effective solutions to reduce the risks. Help in the event of an accident. This research aims to improve the level of safety and durability of earthen dams against these explosions. [3-13] In the continuation of the research, using Abaqus modeling and numerical analysis using the Python programming language, the behavior of the injection gallery against the explosion was investigated. Takes Considering the technical specifications of concrete and accurate modeling, the effects of pressure and volume change in the structure of the injection gallery are examined. The main goal of this research is to provide effective methods to reduce the possible risks caused by the explosion in the injection gallery of the earthen dam. By analyzing and checking the results of modeling and numerical analysis, it is possible to propose solutions to strengthen the structure of the injection gallery and reduce the effects caused by the explosion [14,15]. Considering the importance of the issue and the potential of serious explosion risks in earthen dams, this research can help relevant experts and managers in the field of construction and operation of dams. to make better decisions about the design and improvement of dams [16].

2. METHODOLOGY

In this research, the modeling of a reservoir dam located in Lorestan, Iran, is utilized as a case study. The dam is analyzed to understand its structural and hydraulic characteristics, which play a crucial role in its overall performance. Detailed information about the physical dimensions, construction materials, design features, and operational parameters of the dam is provided to facilitate the modeling process. These general characteristics, which form the basis for the analysis and simulation of the dam, are

thoroughly outlined and presented in [Tables 1](#) and [2](#). The tables include specific data such as the dam's height, storage capacity, type of construction, geological conditions, and other relevant factors that are critical for accurate modeling and assessment of its stability, efficiency, and safety under various conditions. This data serves as the foundation for further computational studies, simulations, and assessments conducted as part of this research.

Table 1. general specifications of Makhmalkoh Reservoir Dam

A pebble with a clay core	dam type
1419meters above sea level	The amount of the river bed at the dam site
53meters	The maximum height of the dam from the river bed
663meters	The length of the crest of the dam
1472meters above sea level	The number of Taj Dam
1469meters above sea level	The normal amount of dam operation
33million cubic meters	The volume of the tank is in the amount of normal operation
0 / 182million cubic meters	Volume of 50year sediments-
60million cubic meters	Annual adjustable water
721001cubic meters	Body embankment volume
996000cubic meters	Excavation

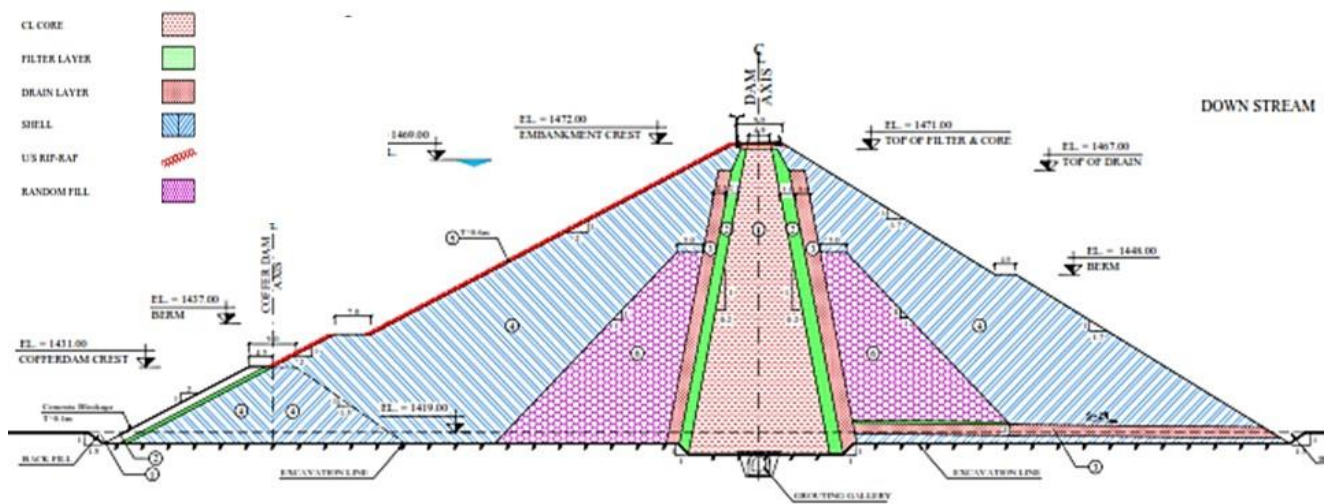


Figure 1. Details of Makhmalkoh dam wall

As detailed in [Table 1](#), the injection gallery has a total length of 900 meters and is constructed using reinforced concrete. This gallery serves a critical function in the dam's structural integrity and operational efficiency, facilitating the controlled injection of materials or fluids. The use of concrete and reinforcement ensures its durability and strength, enabling it to withstand various pressures and

environmental factors. The design and layout of the injection gallery, including its structural components, are illustrated in the figure below, providing a visual representation of its construction and positioning within the dam. This figure helps clarify the gallery's role and integration with the overall dam infrastructure.

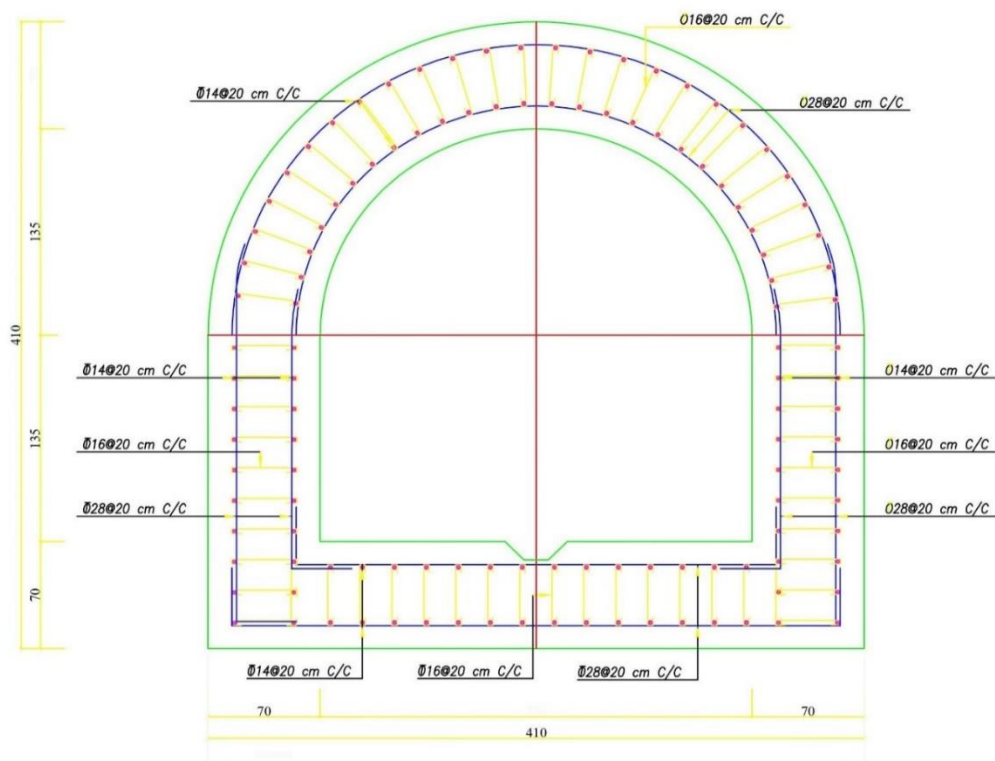


Figure 2. cross-section of the injection galler

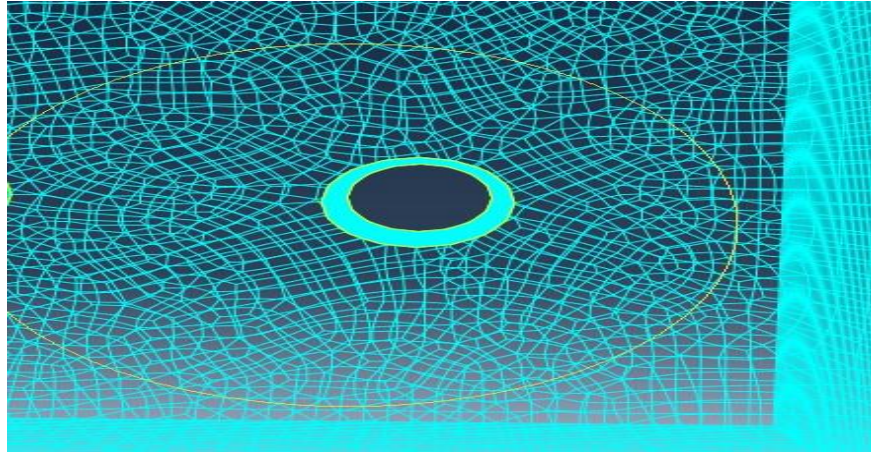


Figure 3. Meshing of the dam injection gallery area

In an explosion, energy is produced and released rapidly, resulting in gas production and rapid volume expansion. This process causes a pressure wave to spread outward from the center of the explosion. This pressure wave can destroy buildings and other structures [3].

$$E = m \times Q$$

Where in E explosion energy, m is the mass of the explosive material and Q is the explosive energy for the material used.

This energy causes gas production and rapid volume increase. The pressure caused by this gas can be

calculated using the ideal gas law and the following formula: [1]

$$P = VE$$

This pressure produces a pressure wave that spreads outward from the center of the explosion. The speed of this pressure wave can be calculated using the following formula: [5,7,9,6]

$$v = \sqrt{\frac{E}{\rho}}$$

Where in v the velocity of wave propagation, E explosion energy and ρ is the density of the environment. [12,4,9]

Table 2. Technical specifications of concrete used in injection and modeling gallery in Abacus

f_c (MPa)	48
T (MPa)	4
ϵ_0	1
E_{fmin}	0.01
S_{fmax}	7
S_{fmax}	7
P_{crush} (MPa)	16
l_{crush}	0.001
P_{lock} (GPa)	0.8
l_{lock}	0.1

3. RESULTS AND DISCUSSION

With 800 tons of TNT spread evenly in the tunnel, the total energy of the explosion can be calculated using the following formula: [5-8-16-9]

$$\sigma = \frac{E}{\rho} \times v$$

Where σ is the stress on concrete (in megapascals), E is the blast energy (in joules), ρ is the concrete density

(in kilograms per cubic meter) and v is the wave propagation speed (in meters per second). By inserting the given values, we have: [5,8,9,16]

$$\sigma = \frac{800 \times 10^6 \times 4.184}{2400} \times \sqrt{\frac{800 \times 10^6 \times 4.184}{2100}}$$

$$\sigma = 1.63 \times 10^4$$

So, the stress in concrete is approximately 16300 MPa.

Stress in the injection gallery: Assuming that the injection gallery is a circular pipe, the stress in the injection gallery can be calculated using the following equation

$$\sigma = \frac{P \times r}{t}$$

where σ is the stress in the injection gallery (in megapascals), P is the gas pressure (in pascals), r is the inner radius of the pipe (in meters) and t is the thickness of the pipe wall (in meters). By substituting the given values, we have:

$$\sigma = \frac{\frac{800 \times 10^6 \times 4.184}{900}}{0.05}$$

$$\sigma = 7.43 \times 10^5$$

So, the stress in the injection gallery is about 743000 MPa.

Wave speed: We have already calculated the speed of wave propagation using the following equation:

$$v = \sqrt{\frac{E}{\rho}}$$

where v is the velocity of wave propagation (in m/s) E is the explosion energy (in Joules) and ρ is the density of the clay (in kg/m³) By substituting the given values, we have:

$$v = \sqrt{\frac{800 \times 10^6 \times 4.184}{2100}}$$

$$v = 1.22 \times 10^3$$

So the speed of wave propagation is approx 1220 meters per second.

Shock effect: The shock effect can be calculated using the following equation:

$$I = \frac{E}{A}$$

where I is the shock effect (in joules per square meter) E is the explosion energy (in joules) and A is the contact area between the explosive and the clay (in square meters). By substituting the given values we have:

$$I = \frac{800 \times 10^6 \times 4.184}{\pi \times 0.05^2}$$

$$I = 4.23 \times 10^{11}$$

So the shock effect is about 423,000 megajoules per square meter I_s .

Stress caused by water exit: The stress caused by water exit can be calculated using the following equation:

$$\sigma = \rho \times g \times h$$

at that σ ,the stress due to water exit (in pascals) ρ ,water density (in kg/m³) g Acceleration of gravity (in m/s/s) and h .is the water level height (in meters) By substituting the given values, we have:

$$\sigma = 1000 \times 9.81 \times 50$$

$$\sigma = 4.91 \times 10^5$$

So, the stress caused by water exit is approximately 491,000 Pascals I_s .

In general, the shock wave increases the pressure and temperature in the clay. This increase in pressure and temperature can have different effects on the water content of clay. Some of these effects are:

Shrinkage of clay: As the pressure increases, the empty volume between the clay particles decreases and causes the clay to shrink. This contraction causes pressure on the water inside the voids and may direct the water towards the surface or cracks of the clay. Therefore, the water content is lower at points further away from the shock source.

Water heating and evaporation: As the temperature increases, the water inside the voids of the clay heats up and may turn into steam. This evaporation reduces the water content and increases the gas pressure in the voids. Therefore, the water content in the points close to the shock source decreases.

Diffusion and absorption of water: By producing pressure and temperature gradients in clay, water may move through the voids of clay as diffusion or absorption. Water diffusion means the movement of water from points of higher pressure to points of lower pressure. Absorption of water means movement of water to places with lower

temperatures. These movements cause changes in the distribution and content of water in the clay.

Using Langevin's formula, the change in water content can be calculated using void permeability and shock pressure. For this, we must first calculate the shock pressure using the following equation: [15-8-9,5]

$$P = \frac{E}{V}$$

Where P is the shock pressure (in pascals), E is the energy of the explosion (in joules) and V is the volume of the space in which the gas is expanded (in cubic meters). By substituting the given values, we have : [9-15-16]

$$P = \frac{800 \times 10^6 \times 4.184}{900}$$

$$P = 3.72 \times 10^6$$

So the shock pressure is approximately 3,720,000 pascals Is.

Now, by placing the shock pressure and the permeability of voids in the Langevin formula, we have

$$\Delta\theta = -\frac{k}{\rho_w g} \Delta P$$

$$\Delta\theta = -\frac{1.0 \times 10^{-9}}{1000 \times 9.81} \times 3.72 \times 10^6$$

$$\Delta\theta = -3.79 \times 10^{-4}$$

So the change in water content is approx -0.038 percent Is. This means that the water content in the clay is slightly reduced.

Using Goodfroy's formula, the change in water content can be calculated using void density and shock temperature. For this, we must first calculate the shock temperature using the following equation: [5-9-16]

$$T = \frac{E}{C_p m}$$

Where T is the shock temperature (in Kelvin), E is the explosion energy (in Joules), Cp is the heat of absorption of clay (in JK/kg) and m is the mass of clay (in kg). By substituting the given values, we have:

$$T = \frac{800 \times 10^6 \times 4.184}{900 \times 2100}$$

$$T = 1.66 \times 10^3$$

So the shock temperature is approx 1660 Kelvin Is.

$$\Delta\theta = -\frac{\rho_v}{\rho_w} \Delta T$$

$$\Delta\theta = -\frac{1.0}{1000} \times 1.66 \times 10^3$$

$$\Delta\theta = -1.66$$

So the change in water content is approx -166 percent Is. This means that the water content in the clay is significantly reduced.

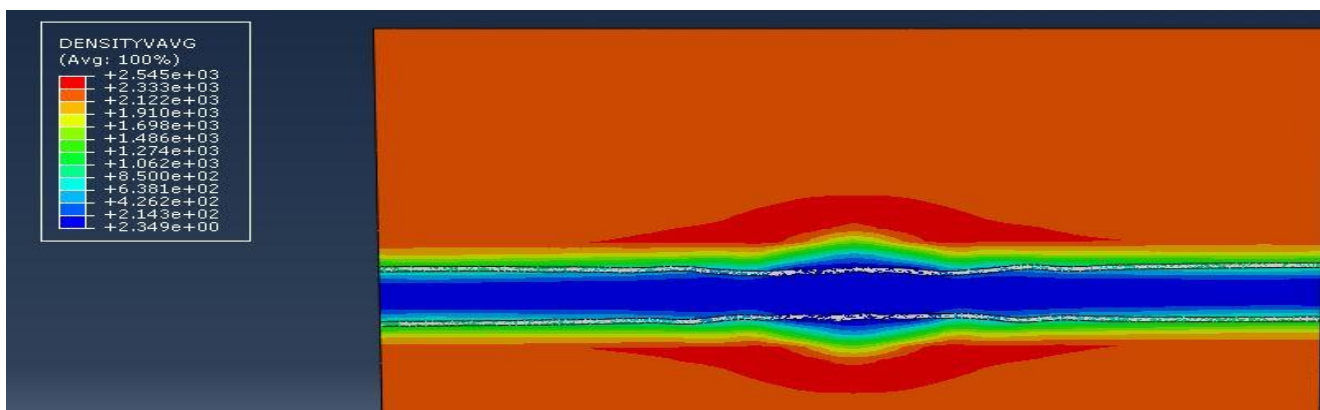


Figure 4. Horizontal section of the stress shape in the injection gallery tunnel

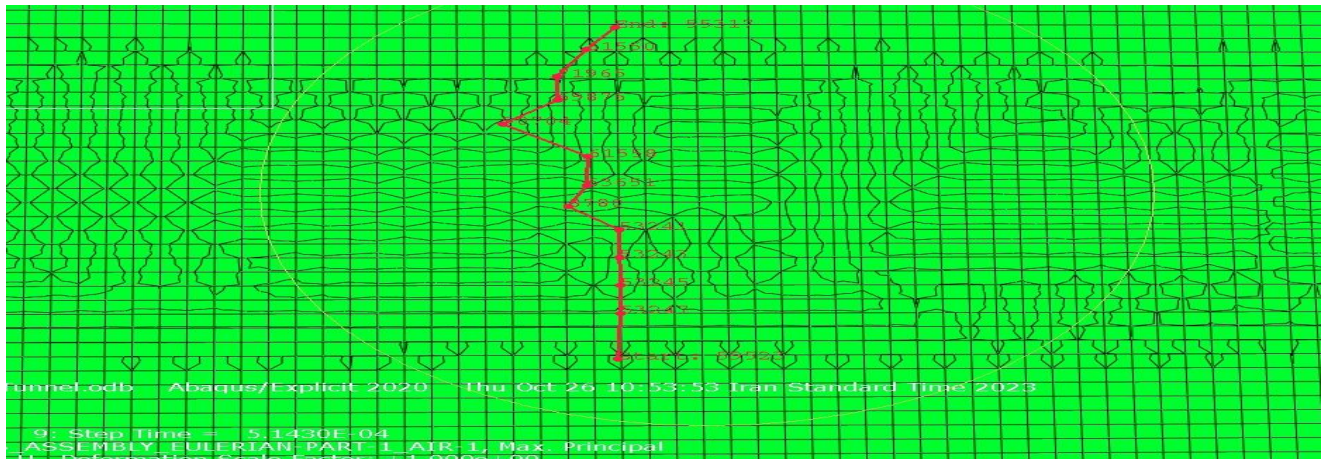


Figure 5. Percentage of strain motion of explosion energy in the upper wall of the dam body

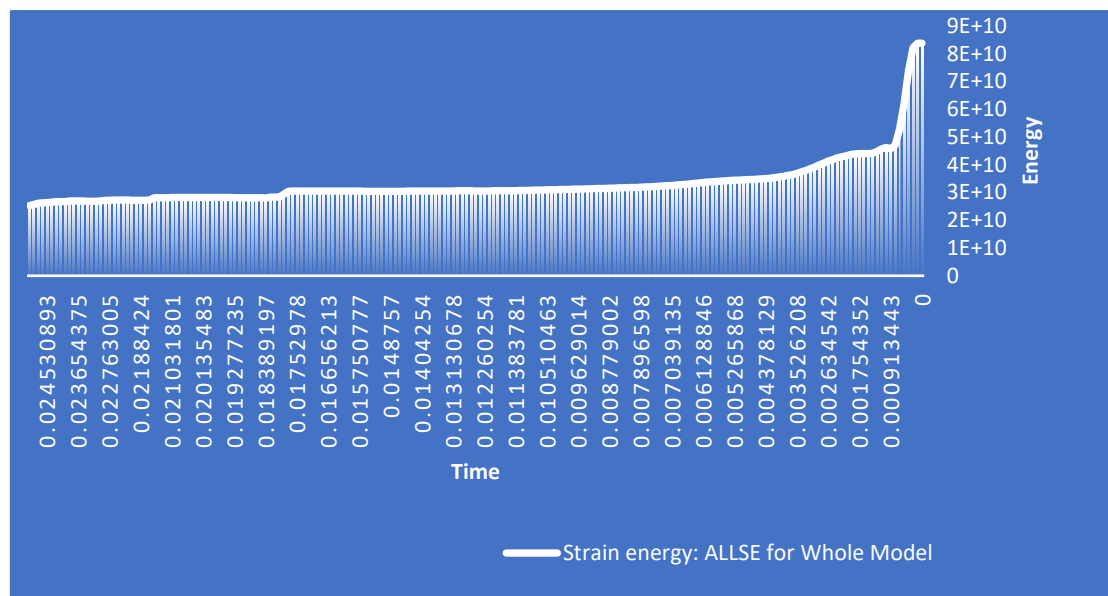


Figure 6. Explanation of dynamic stress during the initial duration of the explosion in the gallery

In the diagram, the number is described as follows

At zero time, the strain energy is equal to $9 \text{ E}+10$ bar. This means that the body has not yet been subjected to any tension and the energy stored in it is at its highest level.

In 0.25 seconds, the strain energy is reduced to $7 \text{ E}+10$ times. This means that the body begins to change shape and part of the energy stored in it is converted into heat and sound.

In 0.5 seconds, the strain energy is reduced to $5 \text{ E}+10$ times. This means that the object has bigger cracks and cracks, and a larger part of the energy stored in it is lost.

At 0.75 seconds, strain energy to $3 \text{ E}+10$ The load is reduced. This means that the object is close to breaking and only a small part of the energy stored in it remains.

In 1 second, the strain energy reaches zero. This means that the object is completely broken and has no energy stored in it.

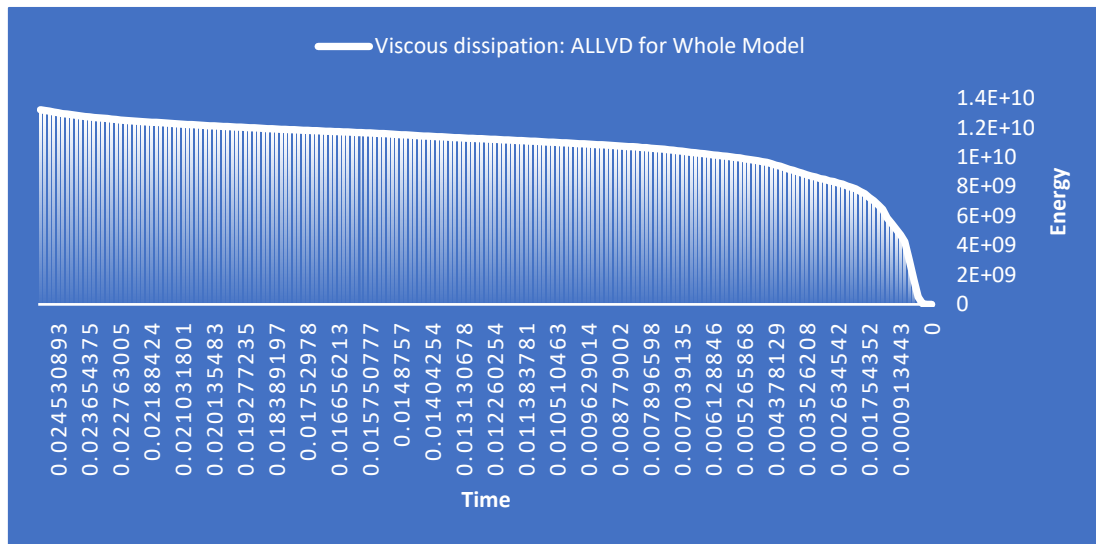


Figure 7. Explanation of elastic stress during the initial duration of the explosion in the gallery

This diagram shows the energy converted into heat as a result of friction in an elastic body that is under stress.

At zero time, the energy converted to heat is equal to $1.2 \text{ E}+11$ bar. This means that the body has not yet been subjected to any tension and the energy stored in it is at its highest level.

In 0.25 seconds, the energy converted to heat is $9.6 \text{ E}+10$. The load is reduced. This means that the body begins to change shape and part of the energy stored in it is converted into heat and sound.

In 0.5 seconds, the energy converted to heat is reduced to $7.2 \text{ E}+10$ bar. This means that the object has bigger cracks and cracks and a larger part of the energy stored in it is lost.

In 0.75 seconds, the energy converted to heat is reduced to $4.8 \text{ E}+10$ times. This means that the object is close to breaking and only a small part of the energy stored in it remains.

In 1 second, the energy converted into heat reaches zero. This means that the object is completely broken and has no energy stored in it.

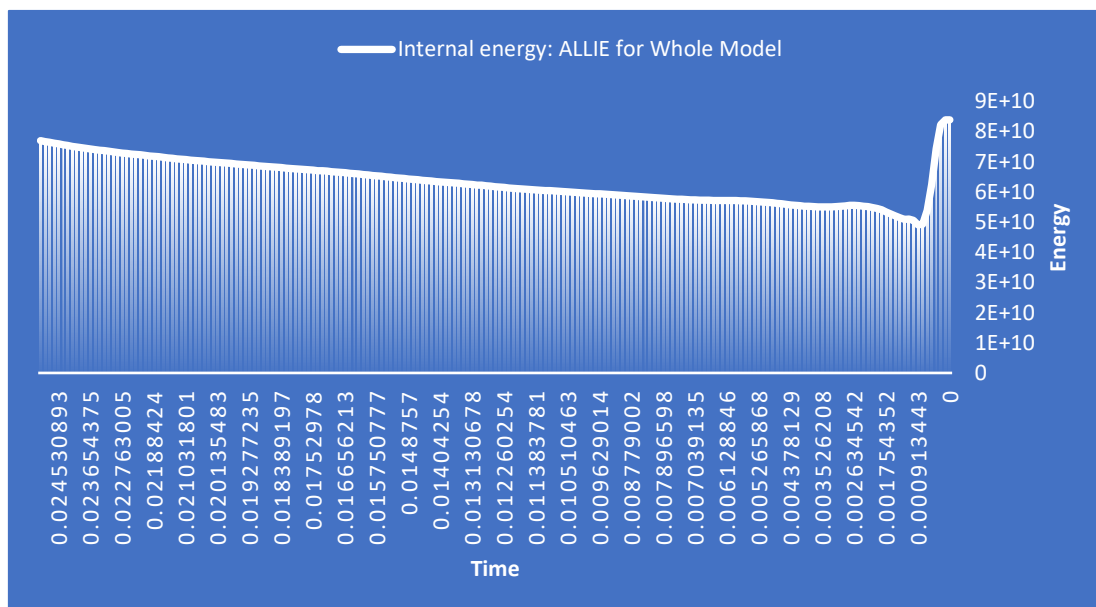


Figure 8. Explanation of the energy at the focal point of the dam body explosion

This graph shows the internal energy of a general model over time. Internal energy is the microscopic energy found in matter, which is defined by the irregular and random movements of molecules and atoms. This diagram is using Abaqus

2 software. A finite element analysis software has been developed. The graph has two horizontal and vertical axes. The horizontal axis represents time, and the vertical axis represents energy. The blue line on the graph represents the internal energy at any

time. This energy increases strongly at first and then gradually decreases and finally increases strongly again. This is because the dam was affected by the explosion and a larger part of the energy stored in it was converted into heat and sound.

At zero time, the internal energy is zero. This means that the dam has not yet been subjected to any stress and no energy stored in it has been converted.

In 0.224707 seconds, the internal energy reaches 9 E+10 times. This means that the dam has reached a crisis state and the largest amount of energy stored in it has been converted into heat and sound.

In 0.449414 seconds, the internal energy is reduced to 7E +10 times. This means that the dam has bigger cracks and cracks, and the second section has become the largest amount of energy stored in it.

In 0.674121 seconds, the internal energy is reduced to 5 E+10 times. This means that the dam is close to breaking and only a small part of the energy stored in it remains.

In 0.898828 seconds, the internal energy is reduced to 3E +10 times. This means that the dam undergoes

major fractures, and another part of the energy stored in it is transformed.

In 1.123535 seconds, the internal energy is reduced to 1 E+10 bar. This means that the barrier is completely broken and only a small part of the energy stored in it remains.

In 1.348242 seconds, the internal energy reaches zero. This means that the dam has no energy stored in it and all its energy has been converted into heat and This graph shows the energy transformed into plastic form in a general model over time. Plastic energy is the energy required to permanently change the shape of a material. This diagram is using Abaqus 1 software. A finite element analysis software has been developed. The graph has two horizontal and vertical axes. The horizontal axis represents time and the vertical axis represents energy. The white line on the graph represents plastic energy at any time. It can be seen that this energy is initially high and then gradually decreases. This is because the dam has been affected by the explosion and a larger part of the energy stored in it has become plastic.

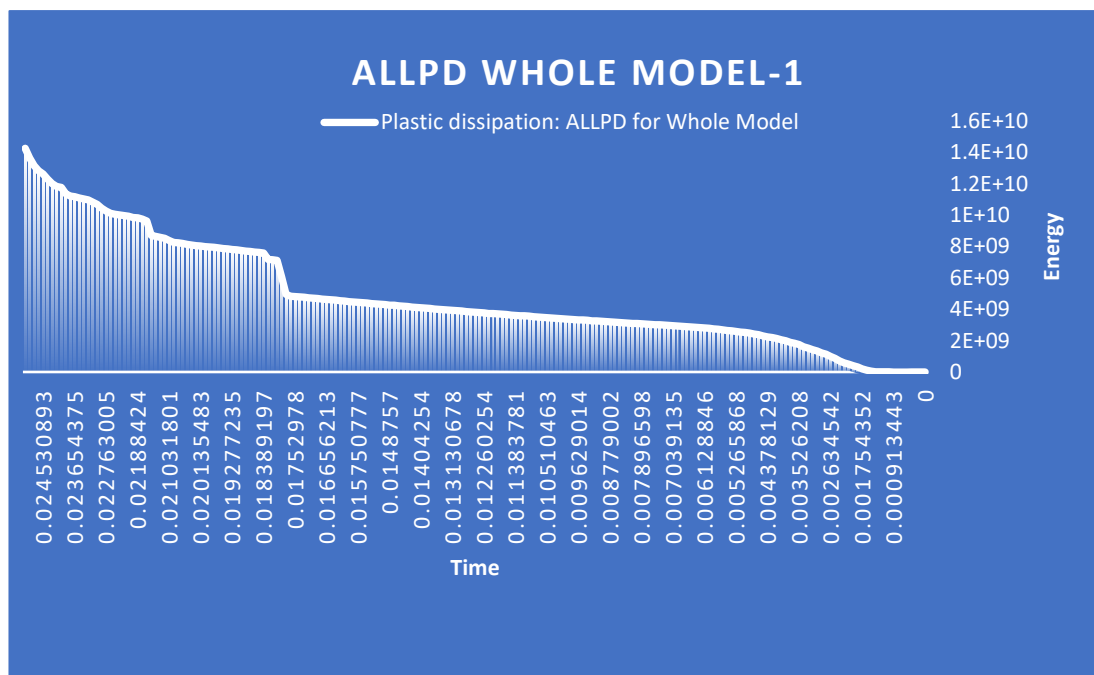


Figure 9. Explanation of plastic stress in the upper wall of the dam

Numerically, we can say that :

At time zero, the plastic energy is equal to 1.6 E+10 bar. This means that the dam is not yet under any stress and all the energy stored in it is elastic.

In 0.224707 seconds, the plastic energy is reduced to 1.4 E+10 bar. This means that the dam starts to form

and the smallest amount of energy stored in it has become plastic.

In a time of 0.449414 seconds, the plastic energy is reduced to 1.2 E+10 bar. This means

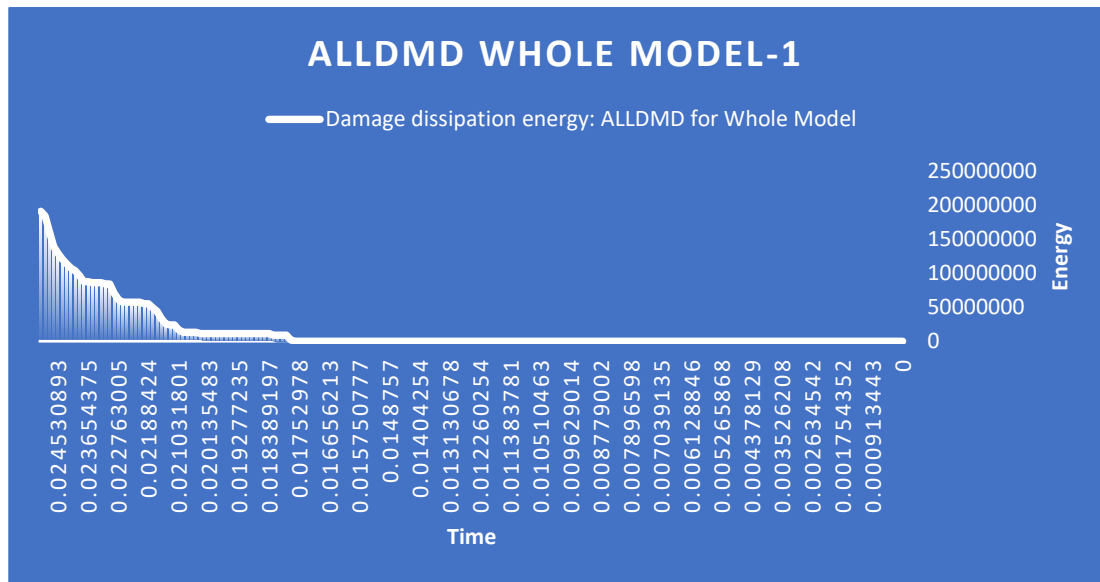


Figure 10. Diagram showing the displacement of the dam body above the crest at a height of 52

This diagram shows the energy converted into heat due to a fracture in an earth dam that has been subjected to explosion. This diagram is using Abaqus 1 software. A finite element analysis software has been developed. The graph has two horizontal and vertical axes. The horizontal axis represents time and the vertical axis represents energy. The white line on the graph represents the energy converted to heat at any given time. It can be seen that this energy reaches its highest level at about 0.25 seconds and then decreases steadily. This is because the barrier begins to break and a larger part of the energy stored in it has been converted into heat and sound.

Numerically, I can say that :

At zero time, the energy converted into heat is zero. This means that the dam has not yet been subjected to any stress and no energy stored in it has been converted.

In 0.25 seconds, the energy converted into heat reaches 2.5×10^7 times. This means that the dam has reached a crisis state and the largest amount of energy stored in it has been converted into heat and sound.

In 0.5 seconds, the energy converted to heat is reduced to 2×10^7 times. This means that the dam has bigger cracks and cracks, and the second section has become the largest amount of energy stored in it.

In 0.75 seconds, the energy converted to heat is reduced to 1×10^7 times. This means that the dam is close to failure.

For the numerical analysis and stress distribution at the height of the dam, a smooth particle hydrodynamics (SPH) method was used, which can be analyzed according to the characteristics of the materials and materials in the table below [\[4,8,6\]](#).

Tale 3. Technical specifications of materials used for explosions

Properties of explosives	
Specification	the amount of
density	65.1grams per cubic centimeter
The energy of the explosion	643megajoules / kg
Mie- Gruneisen equation of state	$A= 8.373 B , = 3.743 , R1 = E0,4.56= 6.9443 _ \text{ megapascal } ^4$
Properties of explosives	
Specification	the amount of
density	65.1grams per cubic centimeter
The energy of the explosion	641.3megajoules / kg
Mie- Gruneisen equation of state	$A= 8.37 B , = 3.74R , 1 = 5.4 E , = 6.94_ _ _ _ \text{ megapascal } ^4$

Table 4. Properties of Soil

Properties of clay	
characteristic	the amount of
density	1 .654grams per cubic centimeter
Modulus of elasticity	10000kilopascals
Poisson's ratio	0.3
Coefficient of internal friction	27degrees
Dilatancy angle	10degrees

Mass conservation equation:

$$\frac{d\rho_i}{dt} = \sum m_j(\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla W_{ij}$$

Equation of motion :

$$\frac{d\mathbf{v}_i}{dt} = \sum_{j=1}^N m_j(\mathbf{f}_i + \mathbf{f}_j) \cdot \nabla W_{ij} + \mathbf{g}$$

artificial force

$$\mathbf{f}_{ij} = \begin{cases} -a \frac{c_{ji} u_{ji}}{p_{ij}} & \text{if } v_{ij} \cdot r_{ij} < 0 \\ 0 & \text{otherwise} \end{cases}$$

Artificial parameters:

$$c_{ij} = \frac{c_i + c_j}{2}, \rho_{ij} = \frac{\rho_i + \rho_j}{2}, \mu_{ij} = \frac{H \mathbf{v}_{ij} \cdot \mathbf{r}_{ij}}{\mathbf{r}_{ij}^2 + \epsilon H^2}$$

Effective stresses:

$$\mathbf{s}_i = \frac{1}{\rho_i} \sum_{j=1}^N m_j(\mathbf{v}_i - \mathbf{v}_j) \otimes \nabla W_{ij}$$

Effective strains:

$$\mathbf{e}_i = \frac{1}{2}(\mathbf{s}_i + \mathbf{s}_i^T)$$

Turkish:

$$f(\mathbf{s}_i) = 0$$

Border:

$$\mathbf{v}_i = 0, \mathbf{f}_i = 0$$

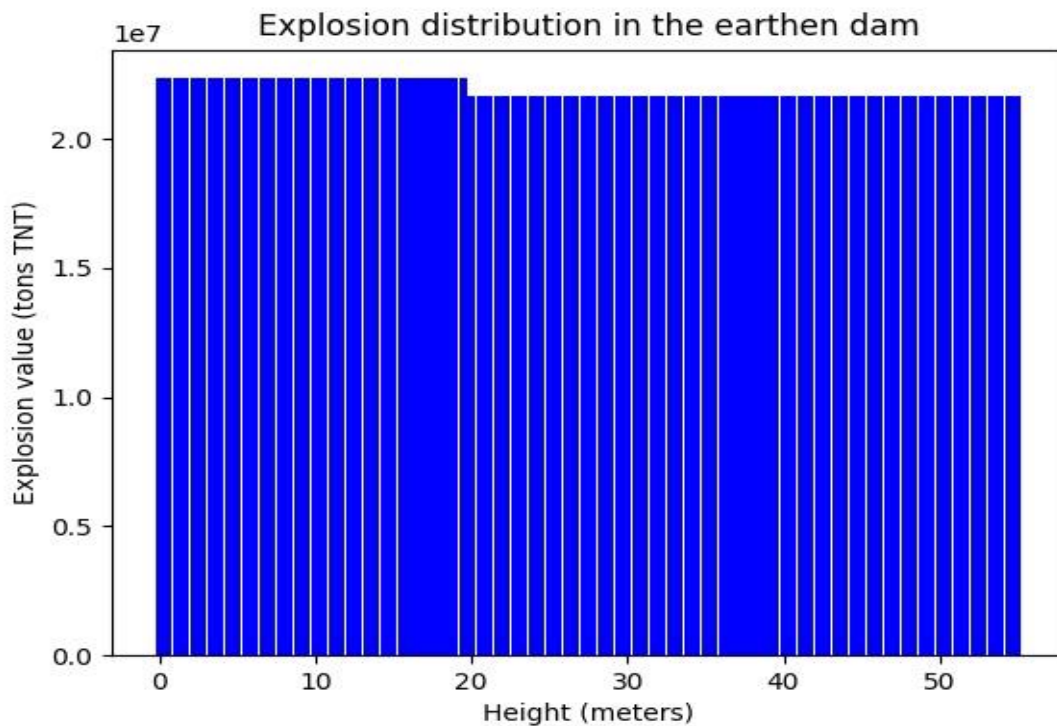


Figure 11. Deviation diagram created in numerical analysis

According to the numerical analysis of the method (SPH), the graph shows that the amount of explosion increases forever with the increase in height from 20 meters number. This is the reason that part of the landslide has been replaced by concrete at these heights and the explosive TNT has a higher density. You can see this effect in the polar diagram that I showed you earlier. The graph also shows that

the amount of explosion is less at zero height and more at 55 height. This is the reason that the amount of explosion is calculated in proportion to the weight of the explosive substance in a spherical volume with a radius of 3 meters. At the height of zero, the weight of the explosive is less and at the height of 55 it is more.

4. CONCLUSION

The results of this study demonstrate that explosions in earthen dams convert stored energy into plastic, heat, and sound, with heat energy playing a crucial role in the explosion process. The finite element analysis shows a complex energy conversion pattern, with internal energy initially increasing, then decreasing, and finally increasing again. The SPH method proves effective in analyzing stress, strain, and cracking in the dam, with burst values increasing with height due to the replacement of part of the embankment with concrete and the higher density of TNT explosives.

Comparatively, the article Numerical Analysis of the Effect

of Afterburning on Damage to the Concrete

Structure Under Interior Explosion focuses on the effects of afterburning on pressure, impulse, and structural damage in a reinforced concrete room. Both studies highlight the importance of numerical modeling and experimental validation in understanding the impact of explosions on structures. While your study emphasizes the energy conversion and structural response in earthen dams, the second article provides insights into afterburning effects and their influence on structural damage in confined spaces.

Overall, both studies contribute valuable knowledge to the field of explosion impact analysis, offering

methodologies and results that can be applied to improve the safety and resilience of various structures under explosive conditions. The results of this paper show that the explosion in an earthen dam converts the energy stored in the dam into plastic, heat, and sound. The energy converted to heat increases with time and acts as the main source of the explosion. The energy converted into plastic form decreases with time and acts as a fracture agent in the barrier. In the finite element analysis, it can be seen that the internal energy increases strongly at first and then gradually decreases and finally increases strongly again. This is because the dam was affected by the explosion and a larger part of the energy stored in it was converted into heat and sound. This has caused the wall of the gallery wall to break and the tension in the upper wall of the drain shell and the stone and soil materials in the dam body can be seen

that the energy converted into heat reaches its highest level in about 0.25 seconds and then decreases steadily. This is because the barrier begins to break and a larger part of the energy is stored. It has been converted into heat and sound. The smooth particle hydrodynamics (SPH) method is a suitable numerical method for the analysis of bursting in an earth dam, because it can calculate the distribution of stress, strain, and cracking at the height of the dam, the results of which are that the burst value increases with the height increase from 20 meters to above. because part of the embankment has been replaced by concrete and TNT explosive has a higher density. The amount of explosion is the lowest at zero height and the highest at 55, because the amount of explosion is calculated in proportion to the weight of the explosive substance in a spherical volume with a radius of 3 meters

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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